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FINAL REPORT ON THE START PROGRAMME

Modeling of a hypothetical Dubna-Baikal long-baseline
neutrino accelerator experiment

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Abstract

This report examines the prospects and presents a simulation of a hypothetical Dubna-Baikal long-baseline experiment using GEANT4 software. Neutrino fluxes and cross-sections were calculated, and the number of events was estimated.

1 Introduction

Despite a century of rapid development of particle physics, fundamental questions about the nature of matter still remain unanswered. One of the most intriguing areas remains neutrino physics and the phenomenon of neutrino oscillations, which requires a revision of existing theories.

A neutrino is an elementary particle belonging to the class of leptons; it has no electric charge. Neutrinos have a small mass and interact weakly with matter. There are three flavors of neutrinos: electron ν_e , muon ν_μ and tau neutrino ν_τ and three mass states: ν_1, ν_2, ν_3 , having masses m_1, m_2 and m_3 , respectively. Each neutrino flavor is a superposition of three mass states, a phenomenon called neutrino mixing.

Neutrino oscillations are the transition of one type of neutrino to another. It is important to note that neutrino oscillations are a consequence of neutrino mixing; without mixing, oscillations are impossible.

Parameters that affect the probability of transition from one neutrino type to another - oscillation parameters:

Mass splitting : $\Delta m_{21}^2, \Delta m_{31}^2, \Delta m_{32}^2$

$$\Delta m_{21}^2 \equiv m_2^2 - m_1^2$$

$$\Delta m_{31}^2 \equiv m_3^2 - m_1^2$$

$$\Delta m_{32}^2 \equiv m_3^2 - m_2^2$$

Mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$ – mixing angles linking mass states with flavor states.

CP phase violation δ_{CP}^ν (CP phase) – phase parameter in the Pontecorvo-Maki-Nakagawa-Sakata matrix. CP symmetry violation in neutrino oscillations in vacuum means that the probabilities of neutrino and antineutrino oscillations are not equal.

Neutrino oscillations indicate that neutrinos have mass, which takes the modern understanding of particle physics beyond the Standard Model. Modern physics of neutrino oscillations largely comes down to determining the oscillation parameters, not all of which have been determined so far. Large-scale experiments are being created, designed, and developed around the world to determine the oscillation parameters. These experiments can be divided by the source of the neutrinos: solar, reactor, accelerator. Starting with the first accelerator experiments, such as LSND[1] and KARMEN[2], the studies became larger and more precise. Over the following years, K2K[3], MINOS[4], T2K[5], NOvA[6] have worked or continue to work. Each experiment had its own design features, its own base and its own scientific goals.

This paper proposes a hypothetical experiment with the Dubna-Baikal base (see Fig 1), where the Nuclotron Dubna is chosen as the accelerator and the Baikal-GVD neutrino observatory is chosen as the detector. The experiment base will be about 4000 km, which is a record base to date. The prospects for such an experiment are considered and modeling is performed in Geant4[7][8] and GNA[9].



Figure 1: Base of hypothetical experiment

2 Description of the LHEP accelerator JINR

The LHEP JINR accelerator complex is designed to conduct experiments on accelerated beams of protons and nuclei (up to elements with atomic masses >100) with energies up to 6 GeV/nucleon for heavy particles and up to 12 GeV for protons. The complex includes ion sources, linear accelerators, a Booster, a Nuclotron, a Collider, beam cooling systems, beam transport lines and the infrastructure necessary for its operation. The main accelerator of the LHEP complex is the Nuclotron, a superconducting synchrotron whose main objects of study are quark-gluon plasma and hadron spectroscopy. The current intensity of protons in the beam is $I = 2 \cdot 10^{10}$ particles per cycle. A detailed description of the installation is given in the article [10]. The scheme and view of the accelerator complex are shown in figures 2 and 3.

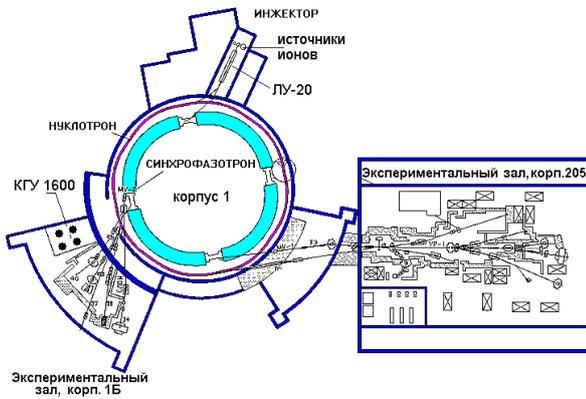


Figure 2: Scheme of the Nuclotron installation



Figure 3: View of the Nuclotron

3 Using the Nuclotron to Create Neutrino Beams

To use the LHEP accelerator as a neutrino source, protons must be accelerated to high energies. Then, protons with energies up to 12 GeV hit the target. Neutrinos are produced as a result of the decay of secondary particles, such as pions π and kaons, which are formed when protons collide with the target. Their decay is accompanied by the production of neutrinos and muons μ , and as a result of the decay of the latter, neutrinos are also produced. The energies of neutrinos depend on the energies of the parent particles (pions, kaons, and muons), which, in turn, depend on the energy of the proton beam and the properties of the target. At a proton energy of 12 GeV, the average energy of secondary pions and kaons is 26 GeV.

4 Description of the Baikal GVD setup

Baikal-GVD (Gigaton Volume Detector) is a deep-sea neutrino telescope designed to detect high-energy astrophysical neutrinos. The experiment consists of clusters of optical modules, each of which consists of 8 vertical strings with photomultiplier tubes (PMTs) (Fig. 4), immersed at a depth of 7501300 m (Fig. 5). Baikal-GVD energy range Baikal-GVD is optimized for detecting neutrinos with energies from 100 GeV to 10 PeV. Neutrinos of such energies create long tracks and cascades that are captured by several detectors. In the low energy region, the telescope operates with low efficiency due to the background of atmospheric neutrinos[11].

The detection principle is as follows: a high-energy neutrino enters the water and as a result of various reactions, secondary high-energy particles are born, which are the source of Cherenkov radiation. Cherenkov radiation in turn enters the photocathode and is converted into a signal using a photomultiplier.



Figure 4: Photomultiplier Baikal GVD

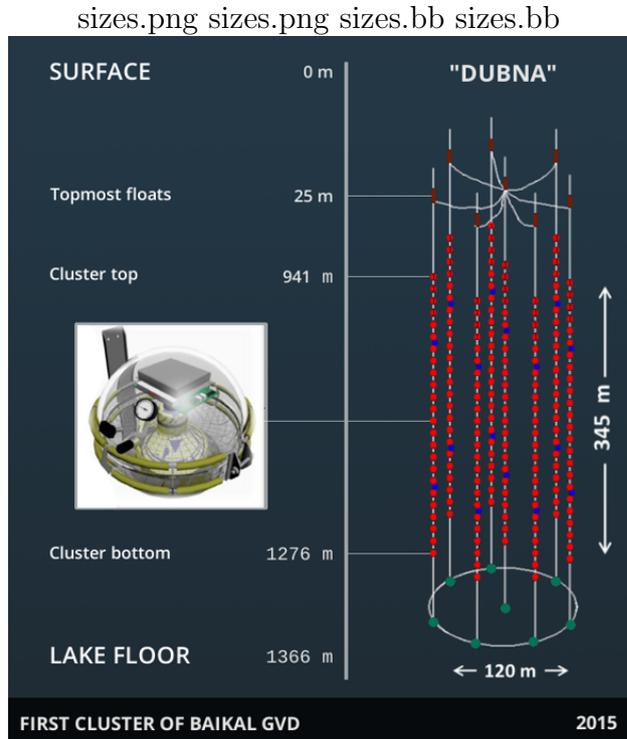


Figure 5: String arrangement diagram

5 Calculation of the neutrino spectrum: qualitative assessment

The production of neutrinos during the reaction is due to the production of pions and kaons and their subsequent decay. Usually, the production and decay of pions makes the largest contribution to the neutrino flux. It will be shown below that the neutrino flux from kaons is insignificant and the main contribution is made by pions.

From the graph it is clear that the contribution of kaons to the production of neutrinos at energies of the order of several GeV is insignificant. Let us consider separately the scenario of kaon and pion production with subsequent decay.

5.1 Pion production and decay

Pions π with an average multiplicity of $n = 3.4$ are produced with a high probability during the interaction of 12 GeV protons¹[12]. We will choose a graphite target (C) as a target.

$$m_{\text{target}} \approx A * M_{\text{nucleon}} \approx 11.3 \text{ GeV}$$

It is convenient to consider the kinematics of the process in the center-of-mass system. The maximum free energy released after the interaction can be calculated using the Mandelstam

¹The average multiplicity is the average number of pions produced from proton tracks registered in the detector.

variables:

$$s = (\Sigma E_i)^2 - (P_i)^2$$

Since the target is at rest:

$$E_{\text{target}}^2 = M_C^2$$

The energy of the proton:

$$E_{\text{proton}}^2 = M_{\text{proton}}^2 + P^2$$

We obtain the value of the Mandelstam variable:

$$s = 2m_p E_p + m_p^2 + m_{\text{target}}^2 \approx 397.6 \text{ GeV}$$

$$\sqrt{s} = \sqrt{2m_p E_p + m_p^2 + m_{\text{target}}^2} \approx 19.94 \text{ GeV}.$$

Energy available for the production of secondary particles given the mass of the carbon nucleus:

$$E = \sqrt{s} - M_C \approx 8.7 \text{ GeV}$$

It is worth considering that not all free energy goes to the production of pions, some energy also goes to the excitation of nuclei and the production of other particles. Let's call the coefficient of energy spent on the production of pions K . Let's assume that the average energy of a produced pion is 1 GeV. Then, on average, the production of pions requires:

$$E_{\pi \text{sum}} \approx 1 \text{ GeV} * 3.4 = 3.4 \text{ GeV}$$

$$K \approx \frac{3.4}{8.7} * 100 \approx 39\%$$

We assume that the remaining part of the energy is equally redistributed between the produced pions, then the average pion energy, taking into account the average multiplicity:

$$E_{\pi} = \frac{K * E}{n}$$

An example for other multiplicities is presented in the table 1.

Table 1: Average pion energies at different multiplicities

N_{π}	E_{π} (GeV)
1	3.4
2	1.7
3	1.13
4	0.85
5	0.68
6	0.57
3.4	1

Next, we calculate the neutrino energies obtained as a result of pion decay. Formula for neutrino energy depending on pion energy [13].

$$E_{\nu} = \frac{m_{\pi}^2 - m_{\mu}^2}{2\gamma m_{\pi}(1 - \beta \cos \theta)}$$

where:

Muon mass $m_\mu \approx 105\text{MeV}$ Muon mass $m_\pi \approx 140\text{MeV}$ θ is the meson emission angle. Neutrino energy range:

Assuming that the pion energy is much greater than its mass, the formula can be rewritten:

$$E_\nu = \frac{(m_\pi^2 - m_\mu^2) \cdot E_\pi}{m_\pi^2(1 + \frac{E_\pi^2 \theta^2}{m_\pi^2})}$$

The dependence of the mean neutrino energy on the pion energy in the small-angle approximation is presented in Table 2.

Table 2: Average neutrino energies for different E_π

N_π	E_π (MeV)	$\langle E_\nu \rangle$ (MeV)
1	3.4	1.45
2	1.7	0.72
3	1.13	0.48
4	0.85	0.36
5	0.68	0.29
6	0.57	0.24
3.4	1	0.43

6 Neutrino fluxes

6.1 Dependence of the neutrino cross section on energy

The neutrino cross-section values as a function of energy can be modeled using various software tools. The figures 6 and 7 show the modeled cross-section dependences on energy for muon neutrinos and antineutrinos.

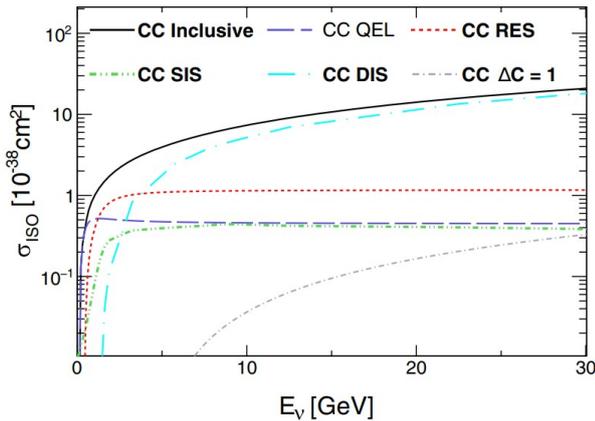


Figure 6: Neutrino cross section as a function of energy[14]

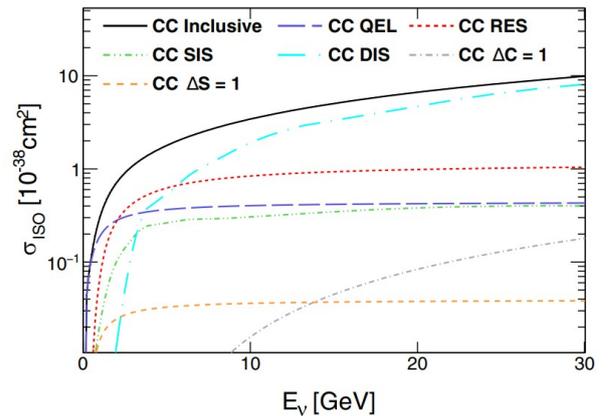


Figure 7: Antineutrino cross section as a function of energy[14]

7 beam trajectory and neutrino flux

The experiment base is 4,2004,300 kilometers. Unlike other neutrino sources, the accelerator particles that reach the telescope will reach the detector in a small range of angles.

Let's take the intensity of protons emitted by the accelerator $10^{12}p/s$. As a result of the interaction of protons with the target, several pions or kaons are born. Let's take the average number of pions produced as a result of interaction - 3, for kaons - 1, then, taking into account the decay probability:

$$\pi : N_{\nu_{\mu}} \approx 10^{12} p/s \times 3 (\pi^+/p) \times 0.5 = 1.5 \times 10^{12} \nu_{\mu}/s.$$

$$K^+ : N_{\nu_{\mu}} \approx 10^{12} \times 0.1 \times 0.5 = 5 \times 10^{10} \nu_{\mu}/s.$$

Let's calculate the angular divergence of the neutrino beam. Let us assume, by analogy with other acceleration experiments, that the beam divergence angle at the beginning is $\approx 2.8^\circ$. Given a distance of 4000 km, the spot will be

$$R = \theta * L \approx 350km$$

. The radius of the Baikal GVD working area is approximately 500m. then

$$S_{detector} \approx 785400m^2$$

$$S_{beam} \approx 3.8 * 10^{11}m^2$$

Then the number of neutrinos arriving in the working area of the detector can be calculated:

$$N_{final} = \frac{S_{detector}}{S_{beam}} * N = 3.1 * 10^6 n/s$$

The cross section of neutrinos with water:

$$\sigma_{H_2O} \approx 4.25 \times 10^{-38} \text{ cm}^2/\text{molecule}$$

To estimate the probability of interaction, we calculate the interaction length λ :

$$\lambda = \frac{1}{n \cdot \sigma}$$

where n is the density of nucleons in water ($\sim 6 \times 10^{23}$ nucleons/cm³).

For $\sigma \approx 4 \times 10^{-38} \text{ cm}^2$:

$$\lambda \approx \frac{1}{6 \times 10^{23} \times 4 \times 10^{-38}} \approx 4 \times 10^{11} \text{ m}$$

Assuming that the detector length is also about 500m.

$$N_{detected} = N_{final} * \frac{500}{4 * 10^{11}} \approx 38.75$$

7.1 Accounting for non-uniform distribution of events

In reality, physical distributions of quantities are not characterized by uniform distribution, let us assume that events are distributed according to the normal distribution (Fig. 8).

$$\frac{dN}{d\theta} = N_0 \cdot \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{\theta^2}{2\sigma^2}\right)$$

Assuming that the standard deviation is 0.33. The fraction of neutrinos passing through the working area of the detector will be 0.005890 In this case, the number of neutrinos passing through the working area

$$N_{final} = 0.005890 * N = 8.835 * 10^9 n/s$$

And the flux will be:

$$\Phi = \frac{N_{final}}{S_{detector}} = 1.13269(\text{cm}^2 * \text{s})^{-1}$$

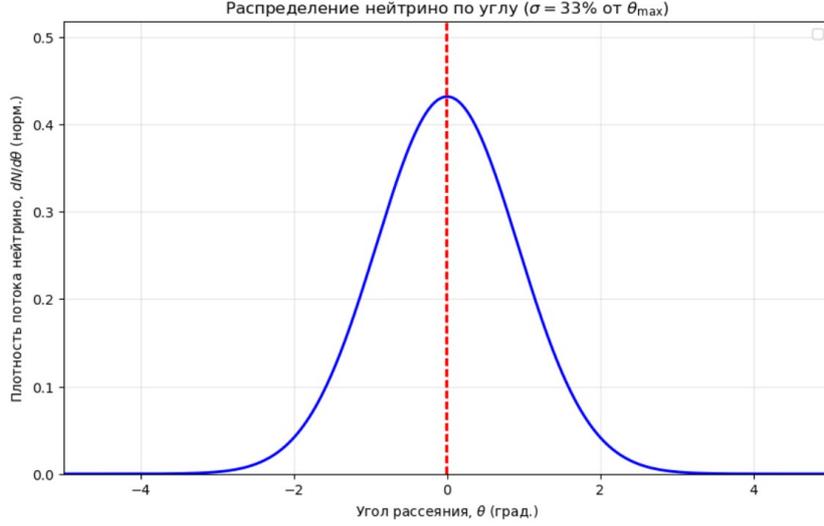


Figure 8: Distribution of events in the beam

7.2 Accounting for oscillations when estimating the number of events

In the original beam, most of the neutrinos are muon neutrinos with a small admixture of electron neutrinos. Cherenkov detectors are mainly sensitive to electron and muon neutrinos, tau neutrinos are practically impossible to detect at these energies, since the taon production threshold is 3.5 GeV. There are two main ways to register neutrino oscillations: registration of electron neutrinos ($\nu_\mu \rightarrow \nu_e$) and registration of the disappearance of muon neutrinos (ν_μ disappearance). In the first method, we neglect electron neutrinos in the original beam. In this case, our goal is to register electron neutrinos in the detector. Let's calculate the number of electron neutrinos taking into account oscillations.

$$N_e^{\text{det}} = N_\mu^{\text{initial}} \times P_{\nu_\mu \rightarrow \nu_e}$$

The probability of a muon neutrino transition to an electron neutrino can be approximately considered equal to[15]:

$$\begin{aligned} P_{\nu_\mu \rightarrow \nu_e} \approx & \sin^2 2\theta_{13} \sin^2 2\theta_{23} \cdot \frac{\sin^2[(A-1)\Delta]}{(A-1)^2} + \\ & + \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \cdot \frac{\sin^2(A\Delta)}{A^2} + \\ & + \alpha \sin 2\theta_{13} \cos(\Delta + \delta_{CP}) \cdot \\ & \cdot \sin 2\theta_{12} \sin 2\theta_{23} \sin(A\Delta) \cdot \frac{\sin[(A-1)\Delta]}{(A-1)A} \end{aligned} \quad (1)$$

Where $A = \frac{2EV}{\Delta}$ In the second approach, it is necessary to compare the muon neutrino spectrum without taking oscillations into account and the experimental data. The number of muon neutrinos taking into account oscillations can be estimated:

$$N_\mu^{\text{det}} = N_\mu^{\text{initial}} \cdot P_{\nu_\mu \rightarrow \nu_\mu}$$

Where the probability of a muon neutrino transition to a muon neutrino can be calculated using the formula[15]:

$$P_{\nu_\mu \rightarrow \nu_\mu} \approx 1 - (\cos^2 \theta_{31} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^4 \theta_{23}) \sin^2 \Delta$$

where $\Delta = \frac{\Delta m_{31}^2 L}{E}$, L is the experimental base. To estimate the probability of neutrino oscillations in matter, we can plot a graph of the oscillation probability as a function of energy for $\nu_\mu \rightarrow \nu_e$ (Fig. 9) for the given experimental base [15].

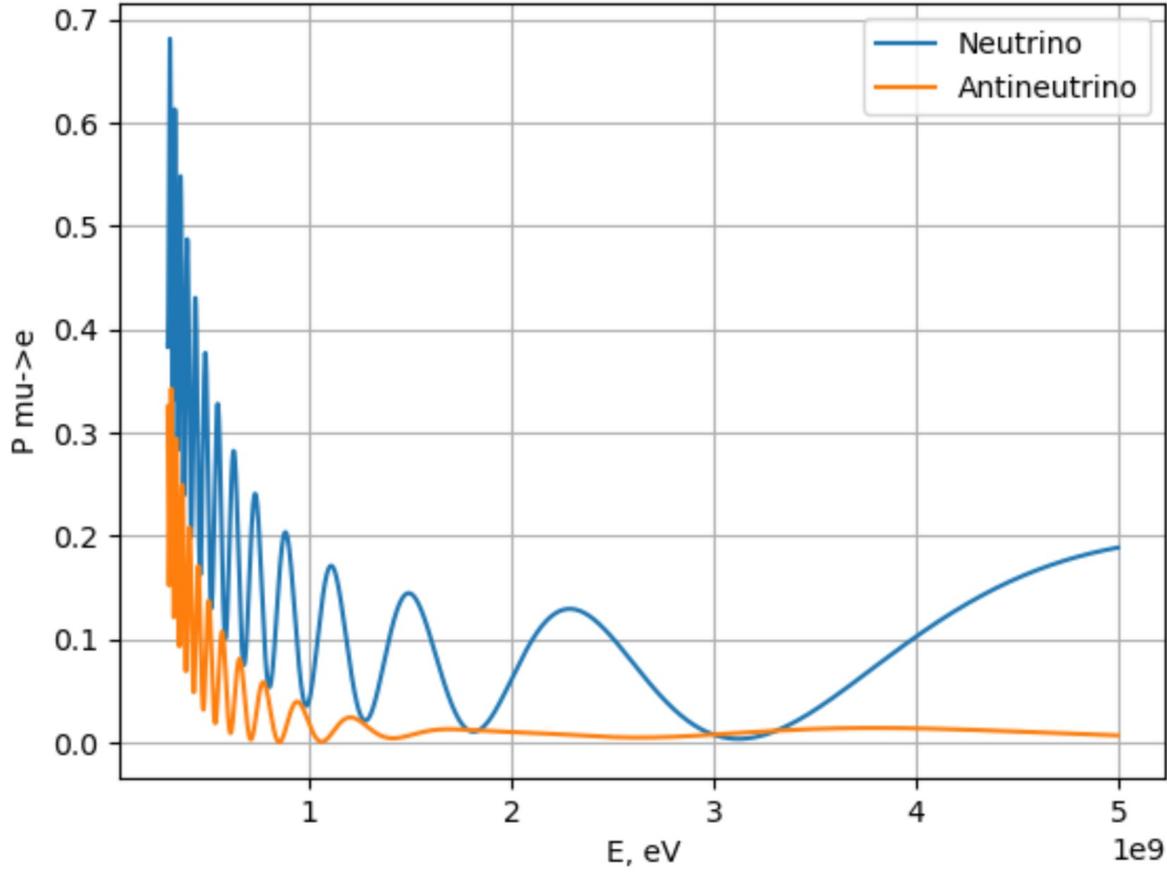


Figure 9: Dependence of the probability of neutrino oscillations on energy

It is evident from the graph that at the energies available to us in the experiment, the probability fluctuates from 0.02 to 0.43. Let us assume that the average probability of oscillation is 0.18, then the number of detected electron neutrinos can be estimated as:

$$N_e^{\text{det}} = N_\mu^{\text{initial}} \times 0.18 \approx 7$$

8 Interaction of neutrinos with water in the working area of the detector

As was said above, Cherenkov radiation comes from high-energy secondary particles. However, the neutrino energies in the experiment under consideration differ significantly from the energies of astrophysical neutrinos. Let us consider in detail the characteristic reactions and signals that can be detected from the neutrino beam from the Nuclotron.

8.1 Processes characteristic of neutrino energies from the accelerator beam

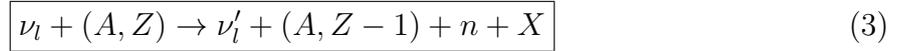
Neutrinos are capable of interacting with matter through a number of processes. The reaction thresholds and cross sections will depend on the neutrino flavor. At energies achievable with the Nuclotron beam, the following processes play a major role:

1. **Inverse beta decay (IBD):**



(threshold ~ 1.8 MeV). As a result of the reaction, the proton is isotropically displaced by several cm and annihilates, while the neutron flies out in the direction of the incoming neutrino, and, experiencing collisions, loses energy and moves within several cm[16].

2. **Reaction with neutron production (on ^{16}O , ^{12}C nuclei):**



where X are possible other products (protons, gamma quanta). The signal from reactions with neutron production is similar to the signal from OBR, but in this case the signal from neutron braking can reach tens of MeV. NC reactions dominate at energies greater than 1.1 GeV.[17].

3. **Electron Scattering (ES):**



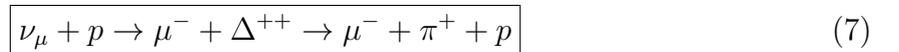
sensitive to all flavors (ν_x), but with different cross sections.

4. **Quasi-elastic (QE) on nucleons:**



is the dominant process up to 1 GeV. The ejected particles create tracks up to several meters long.

5. **Resonance production (Δ -resonance):**



the process dominates in the region after 1.5 GeV and up to 3.5 GeV.

6. **Elastic scattering on nucleons:**



the reaction makes a small contribution to the detected signal.

8.2 Processes Dominant at High Energies

1. Deep Inelastic (DIS):



dominates at $E_\nu > 10$ GeV.

2. Charm quark production:



threshold ~ 10 GeV.

3. Bremsstrahlung (radiative):



The main reactions, energy range and signal characteristics are given in Table 5.

Table 3: Neutrino reaction types and their detection

Reaction type	Energies	Signal (length)
Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$	1-10 MeV	Particles lose energy within a few cm. + delayed signal
Neutron-producing $\nu + (A, Z) \rightarrow \nu' + (A, Z)^* + n$	10-100 MeV	Neutron loses energy during scattering from a few cm to a few m.
Scattering by e^- $\nu + e^- \rightarrow \nu' + e^-$	1 MeV-1 GeV	Short track of e^- (a few cm)
Quasi-elastic (QE) $\nu_\mu + n \rightarrow \mu^- + p$	0.1-10 GeV	Track of μ (up to a few meters) + cascade
Resonance $\nu + N \rightarrow l + \Delta \rightarrow l + \pi + N'$	0.5-10 GeV	Complex signal: long track μ (up to several meters) + particle cascade, short tracks of secondary particles
Deep inelastic (DIS) $\nu + N \rightarrow \nu' + \text{hadrons}$	$\gg 10$ GeV	Cascade (10-20 m) + track μ

The general principle is that at high energies the tracks become longer and hadronic and electromagnetic cascades become more intense [18]. The dependence of the neutrino cross section on the energy for various reactions is shown in the figure 10.

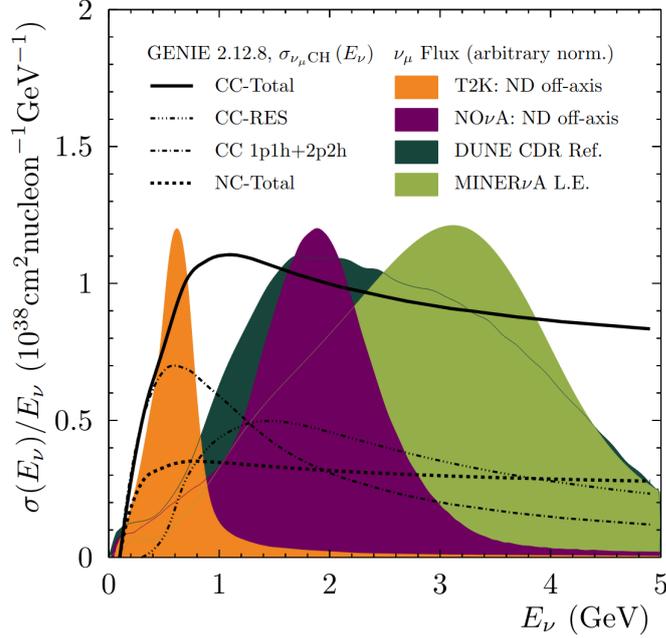


Figure 10: Cross sections of various neutrino reactions [19]

9 Prospects for using Baikal-GVD in an experiment with accelerator neutrinos

As was said, the telescope is capable of detecting neutrino events with high accuracy at energies from 100 GeV, while the energies of the accelerator beam under consideration do not exceed several GeV. The following key ideas can be used to change the telescope's operating range towards lower energies:

- **Increasing the density of PMT strings and the density of PMTs on each string**

Low-energy neutrinos create short tracks and small cascades, so their signal is easily lost in a large-volume detector. In the current Baikal-GVD configuration, the distance between the strings is 60 m. For low-energy neutrinos, this distance should be reduced to increase the probability of detecting weak flashes of light. It is also possible to reduce the distance between the modules on each string (currently 15 m). The optimal distance is 1-2 m, given the characteristic track sizes (1-10 m). The above-mentioned ORCA modification can serve as an example. It is also worth considering the possibility of increasing the number of photomultipliers in the cluster so as not to reduce the working area of the detector; the standard Baikal-GVD cluster has 8 strings with 36 modules.

- **Lowering the PMT response threshold**

The current threshold ($\approx 100 \text{ GeV}$) cuts off low-energy events. To work with accelerator neutrinos (several MeV-GeV), the system needs to be recalibrated.

Figure 11: Physical map of Lake Baikal

- **Using more sensitive PMTs** The design and characteristics of the PMTs in different experiments differ. For example, the PMTs used in the T2K experiment have a lower time resolution, are more compact, have a significantly lower response threshold, but are less sensitive to rare photons. To detect neutrinos with energies of about one GeV, the PMT must have high efficiency in the blue and UV bands, and a large cathode size to capture weak signals.
- **Using Avalanche Detectors** SiPMs are often used to detect low-energy neutrinos (e.g. in the JUNO experiment). They have high sensitivity, but are vulnerable to noise[20].
- **Using Scintillation Detectors** In the range up to hundreds of MeV, scintillators provide better light collection and noise suppression, although they do not determine the direction of tracks. A hybrid system (Cherenkov + scintillation methods) can provide an advantage in the accuracy of event detection.
- **Noise Shielding**
Lead/tungsten shields around clusters to suppress noise from atmospheric muons can help to cut off muon noise, but the implementation of such shielding is associated with great technical difficulties.
- **Improving noise rejection**
Additional muon detectors around the main volume to reject noise.
- **Using underground detectors**
Rocks can provide good protection against atmospheric neutrino noise. The mountainous terrain of Lake Baikal is well suited for placing such a detector (Fig. 11). Example: the T2K concept. Underground detectors also use water purified from microorganisms and radioactive elements, which allows for additional noise reduction.
- **Using improved artificial intelligence models**
Modern machine learning algorithms can improve the efficiency of neutrino event identification by rejecting PMT thermionic noise and bioluminescence noise, without the need to increase the PMT response threshold [21]

10 Overview of similar experiments in structure

At the moment, scientists have data from a number of neutrons. Since the first experiments, such as LSND[1] and KARMEN[2], the experiments have become larger and more efficient. Over the following years, K2K[3], MINOS[4], T2K[5], NOvA[6] and others have been working. Each experiment had its own structural features, its own base and its own scientific goals.

other experiments . The table 4 provides a summary of accelerator experiments on neutrino oscillations with brief information about them.

For further evaluation, it will be useful to consider experiments that are similar in certain parameters.

Table 4: Current and planned experiments on neutrino oscillations. Planned experiments are marked with an asterisk[19]

Experiment	Flavor	Flux Peak (GeV)	Target	Detection
NOMAD	$\nu_\mu, \bar{\nu}_\mu$	10, 5	C	Tracking
K2K	ν_μ	1.3	CH, H ₂ O	Tracking
MiniBooNE	$\nu_\mu, \bar{\nu}_\mu$	0.6, 0.4	CH ₂	Cherenkov
MINOS	ν_μ	3.0	Fe	Tracking
ArgoNeuT	$\nu_\mu, \bar{\nu}_\mu$	6.5, 5.5	Ar	Tracking+Calorimetry
SciBooNE	$\nu_\mu, \bar{\nu}_\mu$	0.6, 0.4	CH	Tracking
T2K off-axis	$\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e^*$	0.6, 0.6, 1, 1	CH, H ₂ O	Tracking
T2K on-axis	$\nu_\mu, \bar{\nu}_\mu^*$	1, 1	CH, H ₂ O*, Fe	Tracking
MINERvA	$\nu_\mu, \bar{\nu}_\mu, \nu_e$	3.5	He*, C, CH, H ₂ O*, Fe, Pb	Tracking+Calorimetry
NOvA*	$\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$	2, *, 1, *	CH ₂	Tracking+Calorimetry
MicroBooNE*	ν_μ	0.6	Ar	Tracking+Calorimetry
ANNIE*	ν_μ	0.6	H ₂ O	Cherenkov
WAGASCI*	$\nu_\mu, \bar{\nu}_\mu$	1, 1	H ₂ O	Tracking
NINJA*	$\nu_\mu, \bar{\nu}_\mu$	1, 1	H ₂ O, Fe	Emulsion

10.1 ORCA/Protvino Experiment

There is one hypothetical experiment with very similar problems - ORCA/Protvino, described in the article [22]. ORCA (Oscillation Research with Cosmics in the Abyss) is a KM3NET collaboration detector located at a depth of more than 2000 meters in the Mediterranean Sea in the south of France. ORCA has a similar design to Baikal-GVD. A cluster of vertical strings with photodetectors strung on them. The distance between the PMTs on the string is 9 m, the distance between the strings is 20 m. The main task of ORCA is to register atmospheric neutrinos with energies of 2-30 GeV. In the case of launching a neutrino beam from the detector in Protvino, the experiment base will be 2595 km. According to the authors of the article, the detector's response depends only on the density of the modules. In order to achieve the required sensitivity and reduce the detection threshold, the authors of the article propose increasing the density of the modules by 10 times. According to calculations, it will be possible to detect about 250 events per year for neutrino energies of about GeV, which is similar to the energies of neutrinos produced in the Nuclotron. The scheme of the experiment is shown in Figure 8.

10.2 K2K

K2K is the first experiment on accelerator neutrinos with a long baseline, was conducted in Japan in 1999-2004. To create a neutrino beam, the KEK accelerator was used, where protons with energies of 12 GeV interacted with a cylindrical aluminum target 66 cm long and 3 cm in diameter, as a result of focusing secondary particles using magnetic horns with a transverse focusing momentum of 100 MeV/c, predominantly muon neutrinos with a flux peak of about GeV were produced[3]. The neutrinos then traveled 250 km to the Super-Kamiokande detector. The Cherenkov detector, scintillation fiber tracker, and muon telescope were chosen as the near detectors. K2K worked primarily on searching for the disappearance of muon neutrinos. Experimental and Geant4-simulated fluxes in the near and far detectors are shown in 12 and

13 [23].

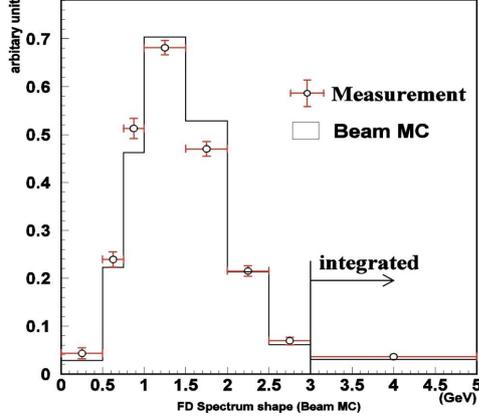


Figure 12: Neutrino flux in the near detector K2K[3]

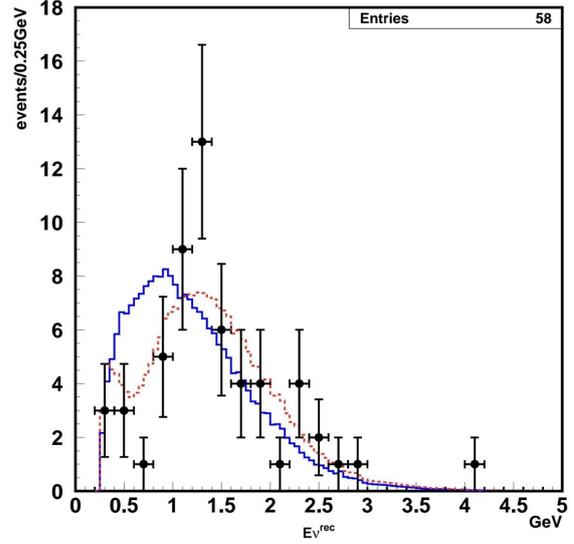


Figure 13: Neutrino flux in the far detector K2K. The solid line shows the expected flux without taking into account the oscillations, the red dots are selected events from the experiment [3]

11 Calculating the neutrino spectrum in the far detector using K2K data

Since the configuration of the K2K experiment is similar to the configuration of our hypothetical experiment, we will try to build a neutrino spectrum and estimate the flux in order to further calculate the sensitivity to the oscillation parameters.

Knowing the formulas for the probability of neutrino oscillations, the neutrino cross section σ (see Fig. 6) and the flux Φ (see Fig. 13) we can estimate the neutrino spectrum in the far detector for searching for electron neutrinos:

$$\frac{dN}{dE} = \Phi \cdot \sigma_{\mu} \cdot P_{\nu_{\mu} \rightarrow \nu_e}$$

And for searching for the disappearance of muon neutrinos:

$$\frac{dN}{dE} = \Phi \cdot \sigma_e \cdot P_{\nu_{\mu} \rightarrow \nu_{\mu}}$$

The spectra are not shown in the figures ?? and ??.

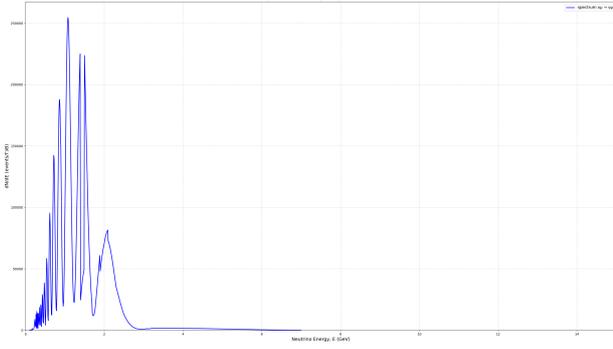


Figure 14:

Figure 15:

12 Neutrino flow simulation using Geant4

Geant4 is a convenient software tool for simulating the passage of particles through matter. In our problem, it is necessary to simulate the interaction of a proton with an energy of up to 12 GeV with a carbon target. The goal is to obtain the dependence of the neutrino flux on energy and calculate the scattering angles.

12.1 Simulation parameters

- **Proton beam**

A 12 GeV proton beam is launched along the axis of the cylinder.

- **Target geometry**

In experiments with accelerators, the target is usually a cylinder with a diameter of several centimeters and a length of several tens of centimeters. I chose the values of radius $r = 1.3$ cm and length $l = 90$ cm by analogy with the T2K experiment (Fig. ??). Pure carbon $^{12}_6C$ was chosen as the target material due to the low mass of the core, wear resistance and plasticity. The target is located 50 cm from the beam launch point.

- **Decay tube** In experiments of this type, pions and kaons pass through a decay tube, where neutrinos are produced during decay reactions. The tube is a cylinder 200 m long and half a meter in radius, such characteristics guarantee that most pions and kaons will have time to decay and will not leave the tube. A vacuum was chosen as the filling material. The tube is located 45 cm from the target.

- **Magnetic horns** For focusing secondary particles, special installations are used - magnetic horns, which create a strong toroidal magnetic field. The horns are set by a current of $I = 250$ kA, which creates a magnetic field inside the volume of the decay tube. The internal radius of the magnetic field is 2 cm, and the external one coincides with the radius of the magnetic tube. When deviating from the beam axis, the Lorentz force begins to act on the particle.

$$F = \frac{qv\mu_0 I}{2\pi r} \quad (12)$$

The schematic device of the magnetic horns in the K2K experiment is shown in the figure 17.

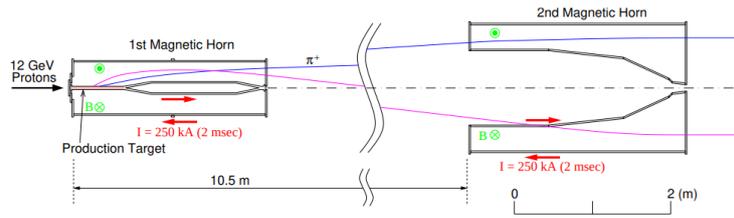


Figure 17: Magnetic horns in the T2K experiment

12.2 Angular distribution

The angular distribution of pions and kaons is shown in figures 18 and 19.

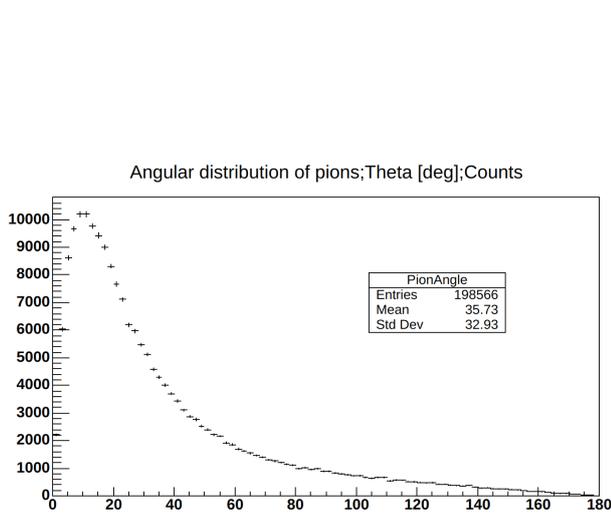


Figure 18: Angular distribution of pions

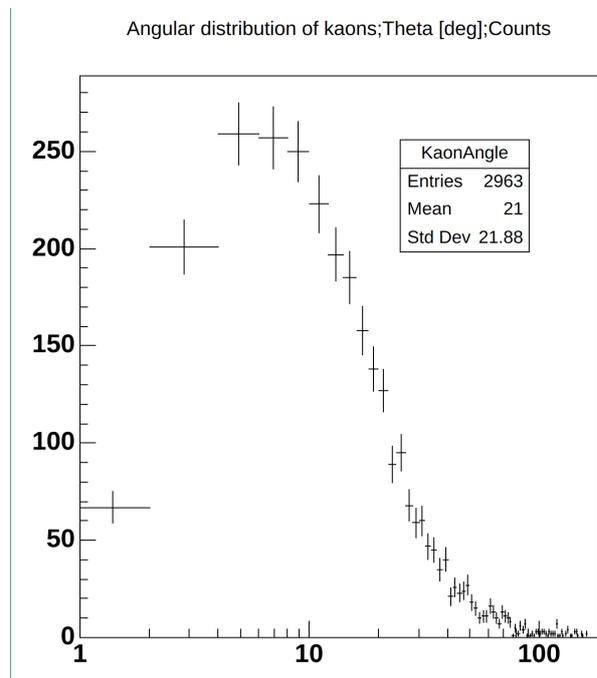


Figure 19: Angular distribution of kaons

Then the muons enter the magnetic horns for focusing.

12.3 Distribution of pions and kaons by energy

distribution of pions and kaons by energy is shown in the figures 20 and 21.

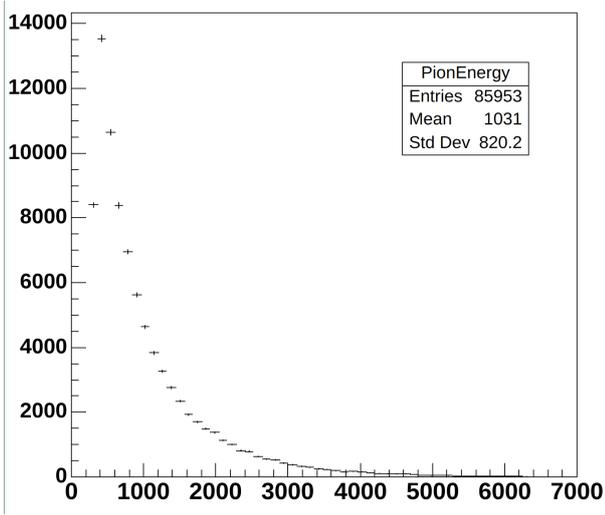


Figure 20: Distribution of pions by energy

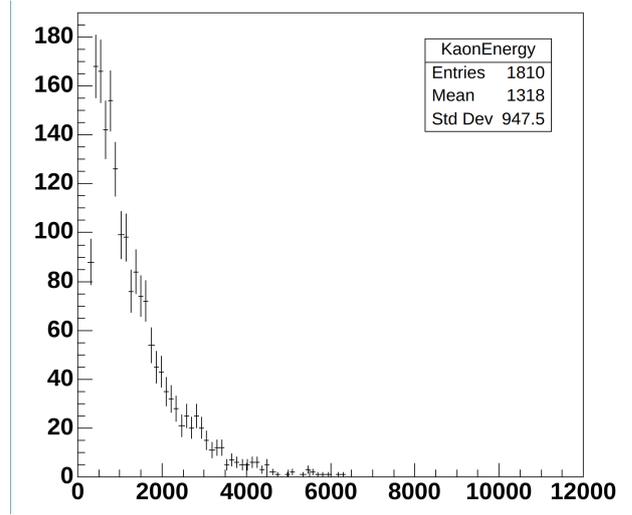


Figure 21: Distribution of kaons by energy

12.4 Ratio of pions and kaons

To estimate the contribution of kaons and pions to the neutrino flux, particle production histograms were constructed (see Fig. 22)

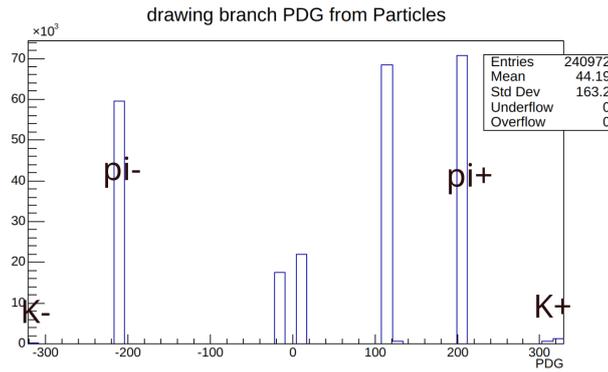


Figure 22: Particle production histogram of a certain type

Thus, the number of kaons is less than two percent of the number of produced particles. The number of π^+ events is several percent greater than π^- events, which agrees with the data modeled in other works[12].

12.5 Neutrino flux

The above reactions produce neutrinos. The neutrino flux is shown in the figure.

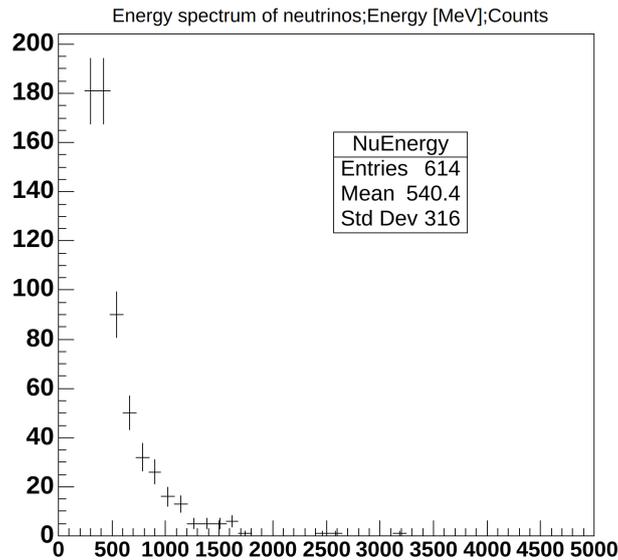


Figure 23: Neutrino flux

13 Conclusion

During the internship, the prospects of a hypothetical experiment with the Dubna-Baikal base were considered, neutrino fluxes and spectra were calculated and modeled.

Judging by the oscillation and spectrum graph, the experiment will probably not be very sensitive to the oscillation parameters, but in the future, due to the modification of the experiment by installing additional detectors with a different base, the experiment may become more promising.

During the internship, I studied in detail the topic of neutrino production in accelerator experiments, proposed possible modifications for the distant detector, mastered and applied the GEANT4 software.

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Whole bibliography

- [1] James E. Hill. “An Alternative Analysis of the LSND Neutrino Oscillation”. In: *Physical Review Letters* 75.14 (Oct. 1995), pp. 2654–2657. ISSN: 1079-7114. DOI: 10.1103/physrevlett.75.2654. URL: <http://dx.doi.org/10.1103/PhysRevLett.75.2654>.
- [2] KARMEN Collaboration. *KARMEN: Present Neutrino-Oscillation Limits and Perspectives after the Upgrade*. 1997. arXiv: hep-ex/9706023 [hep-ex]. URL: <https://arxiv.org/abs/hep-ex/9706023>.
- [3] M. H. Ahn and K2K Collaboration. “Measurement of Neutrino Oscillation by the K2K Experiment”. In: *Phys. Rev. D* 74 (2006), p. 072003. arXiv: hep-ex/0606032 [hep-ex]. URL: <https://arxiv.org/abs/hep-ex/0606032>.
- [4] Justin Evans. *The MINOS experiment: results and prospects*. 2013. arXiv: 1307.0721 [hep-ex]. URL: <https://arxiv.org/abs/1307.0721>.
- [5] K. Abe et al. “The T2K experiment”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 659.1 (Dec. 2011), pp. 106–135. ISSN: 0168-9002. DOI: 10.1016/j.nima.2011.06.067. URL: <http://dx.doi.org/10.1016/j.nima.2011.06.067>.
- [6] Jianming Bian. *The NOvA Experiment: Overview and Status*. 2013. arXiv: 1309.7898 [physics.ins-det]. URL: <https://arxiv.org/abs/1309.7898>.
- [7] S. Agostinelli et al. “Geant4a simulation toolkit”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 506.3 (2003), pp. 250–303. ISSN: 0168-9002. DOI: [https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8). URL: <https://www.sciencedirect.com/science/article/pii/S0168900203013688>.
- [8] J. Allison et al. “Recent developments in Geant4”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 835 (2016), pp. 186–225. ISSN: 0168-9002. DOI: <https://doi.org/10.1016/j.nima.2016.06.125>. URL: <https://www.sciencedirect.com/science/article/pii/S0168900216306957>.
- [9] Joint Institute for Nuclear Research. *Global neutrino analysis Useful links*. http://gna.pages.jinr.ru/gna/useful_links.html. Accessed: 2025-07-25.
- [10] A. D. Kovalenko et al. “The Nuclotron: Present Status and Future Development”. In: *Nuclear Instruments and Methods in Physics Research A* 623 (2010), pp. 291–293. DOI: 10.1016/j.nima.2010.02.209.
- [11] V. A. Allakhverdyan et al. “Overview of the Baikal-GVD neutrino telescope: 2024 status”. In: *EPJ Web of Conferences* 319 (2025). RICAP-24, p. 04002. DOI: 10.1051/epjconf/202531904002. URL: <https://doi.org/10.1051/epjconf/202531904002>.

- [12] M.G. Catanesi et al. “Large-angle production of charged pions by 3GeV/c12GeV/c protons on carbon, copper and tin targets”. In: *The European Physical Journal C* 53.2 (Nov. 2007), pp. 177–204. ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-007-0475-4. URL: <http://dx.doi.org/10.1140/epjc/s10052-007-0475-4>.
- [13] . “ NOvA ”. Russian.. -.:, 2021.
- [14] Jlia Tena-Vidal et al. “Neutrino-nucleon cross-section model tuning in GENIE v3”. In: *Physical Review D* 104.7 (2021). MIT Open Access Articles, Creative Commons Attribution 4.0 International license, p. 072009. DOI: 10.1103/PhysRevD.104.072009. MIT: 1721.1/142000. URL: <https://hdl.handle.net/1721.1/142000>.
- [15] . . . “ 2 NOvA: -”. Russian. In: 161.4 (2022). 3 2021 ., 21 2021 ., 22 2021 ., pp. 515–522. URL: https://jetp.ras.ru/cgi-bin/dn/e_161_04_0515.pdf.
- [16] . “ ”. In: (Jan. 24). URL: <https://www.inr.ru/rus/kud-sem/nik2-18-11-13.pdf>.
- [17] S. Sakai et al. *Measurement of the neutrino-oxygen neutral-current quasielastic cross section using atmospheric neutrinos in the SK-Gd experiment*. 2023. arXiv: 2311.03842 [hep-ex]. URL: <https://arxiv.org/abs/2311.03842>.
- [18] .. Russian.: teach-in, 2020.
- [19] Kendall Mahn, Chris Marshall, and Callum Wilkinson. “Progress in measurements of 0.1–10 GeV neutrino-nucleus scattering and anticipated results from future experiments”. In: *arXiv preprint* (Mar. 2018). arXiv: 1803.08848 [hep-ex]. URL: <https://arxiv.org/abs/1803.08848>.
- [20] Frank Simon. “Silicon photomultipliers in particle and nuclear physics”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 926 (May 2019), pp. 85–100. ISSN: 0168-9002. DOI: 10.1016/j.nima.2018.11.042. URL: <http://dx.doi.org/10.1016/j.nima.2018.11.042>.
- [21] I. Kharuk, G. Rubtsov, and G. Safronov. *Rejecting noise in Baikal-GVD data with neural networks*. 2023. arXiv: 2210.04653 [astro-ph.IM]. URL: <https://arxiv.org/abs/2210.04653>.
- [22] G. Anton A. V. Akindinov1 E. G. Anassontzis. “Letter of interest for a neutrino beam from Protvino to KM3NeT/ORCA”. In: *The European Physical Journal C* 79.758 (2019). DOI: <https://doi.org/10.1140/epjc/s10052-019-7259-5>.
- [23] Joanna Zalipska and K2K Collaboration. “Neutrino Oscillation in the K2K Experiment”. In: *Acta Physica Polonica B* 37.7 (July 2006). Received May 23, 2006, pp. 1969–1980. eprint: hep-ex/0608008. URL: <http://www.actaphys.uj.edu.pl/fulltext?series=Reg&vol=37&page=1969>.